TITLE OF THE INVENTION

INSPECTION APPARATUS USING NUCLEAR MAGNETIC RESONANCE

BACKGROUND OF THE INVENTION

5   The present invention relates to an inspection
apparatus using nuclear magnetic resonance for
acquiring echoes while monitoring motion of a subject
using a nuclear magnetic resonance signal.

          A nuclear magnetic resonance imaging (MRI)
10   apparatus is a medical image diagnosis apparatus which
generates nuclear magnetic resonance in a hydrogen
atomic nucleus in an arbitrary plane across a subject
to acquire a tomographic image in the plane from a
nuclear magnetic resonance signal produced.

15   In general, a slice select magnetic field
gradient specifying a plane to acquire a tomographic
image of a subject is applied, and at the same time, an
excitation pulse exciting spins in the plane is given,
so as to acquire a nuclear magnetic resonance signal
20   (echo) produced in the stage that the spins excited is
refocused. To give position information to the spins, a
phase-encoding magnetic field gradient and a readout
magnetic field gradient in the direction vertical to
each other in a transverse section are applied during
25   the period between the excitation and the echo
acquisition. The measured echo is arranged in a k-space
in which the horizontal axis is kx and the vertical
axis is ky. One echo occupies one line parallel to the

kx axis. The k-space is inverse Fourier transformed to perform image reconstruction.

The pulse and the magnetic field gradient for producing an echo are applied based on a predetermined pulse sequence. Various types of the pulse sequence are known according to an object.

For example, a gradient-echo (GE) method, one of general echo-acquiring methods, is a method which repeatedly operates its pulse sequence to sequentially change a phase-encoding magnetic field gradient for each repetition, thereby successively measuring the number of echoes necessary for acquiring one tomographic image.

FIG. 1(A) shows a pulse sequence of the GE method. The operation of the pulse sequence is as follows. A slice select magnetic field gradient pulse 201 in z direction is applied. At the same time, a radiofrequency magnetic field (RF) pulse 202 for spin excitation having resonance frequency f_0 of a proton is applied. A nuclear magnetic resonance phenomenon is induced in the proton of a certain slice in a subject. A phase-encoding magnetic field gradient pulse 203 for adding position information in a phase-encoding direction (y) to the phase of spin and a readout magnetic fields gradient 205 for dephase are applied. While applying a readout magnetic field gradient pulse 206 for adding position information in a readout direction (x), a nuclear magnetic resonance signal

(echo) 208 is measured. After the echo measurement, a
re-phase magnetic field gradient pulse 207 is applied
to return the phase of the spin for the next excitation.

The procedure from the slice select magnetic
field gradient pulse application to the echo
measurement is repeated in repetition time TR to
measure echoes necessary for acquiring one image. The
echoes are arranged on a k-space 209, as shown in FIG.
1(B), for image reconstruction by two-dimensional
inverse Fourier transform. The echo-acquiring time per
image is 1.28 seconds when at TR of 10ms, an image of
128×128 pixels is acquired. The TR of the sequence is
short. The sequence must be executed above about 20
times until the spin is in a steady state so that the
echoes are stable.

In the case of cardiac imaging, since a cardiac
cycle is about one second which is shorter than the
imaging time, ECG gating is widely used to improve the
time resolution (for example, see "NMR Igaku-Kiso to
Rinsho", published by Maruzen, 1991, pp. 144 to 145).
This method is a method which changes phase encoding in
synchronization with a trigger of R wave of an ECG to
measure echoes necessary for reconstruction of one
image across plural heartbeats. When respiratory motion
occurs during echo-acquiring, a ghost is caused in the
reconstructed image. Echo-acquiring is generally done
during breath-hold.

As an example thereof, FIG. 2(A) shows the

relation between an ECG and measurement when an image of 128×128 pixels is acquired with 8 frames per heartbeat and TR of 5ms. First, phase encoding is changed by 8 immediately after R wave T1 to perform measurement from -64 to 56. This is repeated for 8 frames 8 times. Then, the phase encoding is also changed by 8 immediately after R wave T2 to perform measurement from -63 to 57. This is repeated for 8 frames 8 times. The above measurement is continuously performed to T8. As shown in FIG. 2(B), the echo 208 is rearranged for each of the frames in order of phase encoding to be arranged on the k-space 209 for reconstruction.

There is proposed a method for monitoring breathing using a nuclear magnetic resonance signal. This is a method for detecting motion of the boundary (diaphragm) between a liver and a lung from a one-dimensional projection in an area excited in a rod form from the liver to the lung (see U.S. Patent No. 5,363,844).

In the prior art method for using ECG gating to enhance the time resolution of echo-acquiring, the echo-acquiring time of one image is about 8 seconds for 8 heartbeats. The breath-holding time of a health person is up to about 30 seconds. The number of slices which can be echo-acquired with one breath-hold is about 4 at most. When echo-acquiring the number of slices larger than that, breath-hold must be done

4

plural times. This puts a significant load on a subject.

In the prior art method for monitoring breathing using a nuclear magnetic resonance signal, an echo-acquired section and an excitation area for breathing monitoring are different. Each time breathing monitoring is executed, an extra sequence for returning spin to a steady state must be executed. The echo-acquiring time is longer.

In the prior art, a heart is echo-acquired by ECG gating. An ECG must be worn on a subject.

SUMMARY OF THE INVENTION

An object of the present invention is to provide an inspection apparatus using nuclear magnetic resonance which can execute multi-slice and multi-frame imaging of a heart without giving any load on a subject.

To achieve the above object, an inspection apparatus using nuclear magnetic resonance according to the present invention has static magnetic field generation means generating a static magnetic field; magnetic field gradient generation means generating magnetic field gradients in a first, a second and a third directions orthogonal to each other; radiofrequency magnetic field generation means generating a radiofrequency magnetic field; signal detection means detecting a nuclear magnetic resonance signal (echo) produced from a subject (living body); arithmetic processing means performing arithmetic

5

processing of the detected nuclear magnetic resonance signal; and control means controlling the magnetic field gradient generation means and the radiofrequency magnetic field generation means, wherein the control means executes a pulse sequence acquiring a projection to determine a similarity coefficient between the projection and a reference projection, thereby detecting respiratory motion of the subject.

The control means executes a pulse sequence giving phase encoding to measure an echo while changing the magnitude of the phase encoding for acquiring a tomographic image, acquires the reference projection before executing the pulse sequence, and acquires the projection during execution of the pulse sequence, thereby acquiring an image without the influence of respiratory motion.

An inspection method using nuclear magnetic resonance according to the present invention has the following features.

1) An inspection method using nuclear magnetic resonance having the steps of applying a radiofrequency magnetic field and a magnetic field gradient to a living body placed in a static magnetic field to detect a nuclear magnetic resonance signal produced from the living body and using the detected nuclear magnetic resonance signal to perform image reconstruction of an imaging section, has the steps of: (1) in the state that the living body stops exhalation or inspiration,

executing a first pulse sequence detecting the nuclear magnetic resonance signal to acquire a reference projection of an imaging section as the reference of monitoring of respiratory motion of the living body; (2) in the state that the living body breathes, executing once the first pulse sequence detecting the nuclear magnetic resonance signal to acquire a projection of the imaging section used for the monitoring and in the state that the living body breathes, repeating a second pulse sequence detecting the nuclear magnetic resonance signal to acquire an image of the imaging section at predetermined repetition time intervals; and (3) collecting the nuclear magnetic resonance signals used for the image reconstruction in the second pulse sequence based on a similarity coefficient between the projection and the reference projection.

2) An inspection method using nuclear magnetic resonance having the steps of applying a radiofrequency magnetic field and a magnetic field gradient to a living body placed in a static magnetic field to detect a nuclear magnetic resonance signal produced from the living body and using the detected nuclear magnetic resonance signal to perform image reconstruction of an imaging section, has the steps of: (1) in the state that the living body stops exhalation or inspiration, executing a first pulse sequence detecting the nuclear magnetic resonance signal to acquire a reference

projection of an imaging section as the reference of monitoring of respiratory motion of the living body; (2) in the state that the living body breathes, executing once the first pulse sequence detecting the nuclear magnetic resonance signal to acquire a projection of the imaging section used for the monitoring and in the state that the living body breathes, repeating a second pulse sequence detecting the nuclear magnetic resonance signal to acquire an image of the imaging section at predetermined repetition time intervals; (3) collecting the nuclear magnetic resonance signals used for the image reconstruction in the second pulse sequence by monitoring the motion based on a similarity coefficient between the projection and the reference projection; and (4) repeating the (2) to the (3).

3) An inspection method using nuclear magnetic resonance having the steps of applying a radiofrequency magnetic field and a magnetic field gradient to a living body placed in a static magnetic field to detect a nuclear magnetic resonance signal produced from the living body and using the detected nuclear magnetic resonance signal to perform image reconstruction of an imaging section, has the steps of: (1) in the state that the living body stops exhalation or inspiration, executing a first pulse sequence detecting the nuclear magnetic resonance signal to acquire a reference projection of the imaging section; (2) in the state

that the living body breathes, executing once the first
pulse sequence and in the state that the living body
breathes, repeating a second pulse sequence detecting
the nuclear magnetic resonance signal at predetermined
5   repetition time intervals; (3) acquiring a projection
of the imaging section from the nuclear magnetic
resonance signal detected in the first pulse sequence
of the (2); (4) determining a similarity coefficient
between the projection and the reference projection;
10   (5) monitoring respiratory motion of the living body
based on the similarity coefficient; (6) collecting the
nuclear magnetic resonance signals used for the image
reconstruction in the second pulse sequence according
to the result of the monitoring; and (7) repeating the
15   (2) to the (6).

4) The inspection method using nuclear magnetic
resonance according to the 3), wherein in the (5), the
motion is monitored based on comparison of a value of
the similarity coefficient with a predetermined
20   threshold value.

5) An inspection method using nuclear magnetic
resonance having the steps of applying a radiofrequency
magnetic field and a magnetic field gradient to a
living body placed in a static magnetic field to detect
25   a nuclear magnetic resonance signal produced from the
living body and using the detected nuclear magnetic
resonance signal to perform image reconstruction of an
imaging section, has the steps of: (1) in the state

that the living body stops exhalation or inspiration, executing a first pulse sequence detecting the nuclear magnetic resonance signal; (2) acquiring a reference projection of the imaging section from the nuclear magnetic resonance signal detected in the first pulse sequence; (3) in the state that the living body breathes, executing once the first pulse sequence and in the state that the living body breathes, repeating a second pulse sequence detecting the nuclear magnetic resonance signal at predetermined repetition time intervals; (4) acquiring a projection of the imaging section from the nuclear magnetic resonance signal detected in the first pulse sequence of the (3); (5) determining a similarity coefficient between the projection and the reference projection; (6) collecting the nuclear magnetic resonance signals used for the image reconstruction in the second pulse sequence based on comparison of a value of the similarity coefficient with a predetermined threshold value; and (7) repeating the (3) to the (6).

6) An inspection method using nuclear magnetic resonance having the steps of applying a radiofrequency magnetic field and a magnetic field gradient to a living body placed in a static magnetic field to detect a nuclear magnetic resonance signal produced from the living body and using the detected nuclear magnetic resonance signal to perform image reconstruction of an imaging section, has the steps of: (1) in the state

that the living body stops exhalation or inspiration, executing a first pulse sequence detecting the nuclear magnetic resonance signal; (2) acquiring a reference projection of the imaging section from the nuclear magnetic resonance signal detected in the first pulse sequence; (3) in the state that the living body breathes, executing once the first pulse sequence and in the state that the living body breathes, repeating a second pulse sequence detecting the nuclear magnetic resonance signal at predetermined repetition time intervals; (4) acquiring a projection of the imaging section from the nuclear magnetic resonance signal detected in the first pulse sequence of the (3); (5) determining a similarity coefficient between the projection and the reference projection; (6) collecting the nuclear magnetic resonance signals used for the image reconstruction in the second pulse sequence based on the similarity coefficient; and (7) repeating the (3) to the (6).

7) An inspection method using nuclear magnetic resonance having the steps of applying a radiofrequency magnetic field and a magnetic field gradient to a living body placed in a static magnetic field to detect a nuclear magnetic resonance signal produced from the living body and using the detected nuclear magnetic resonance signal to perform image reconstruction of an imaging section, has the steps of: (1) in the state that the living body stops exhalation, executing a

first pulse sequence detecting the nuclear magnetic resonance signal; (2) acquiring a reference projection of the imaging section from the nuclear magnetic resonance signal detected in the first pulse sequence; (3) in the state that the living body breathes, executing once the first pulse sequence and in the state that the living body breathes, repeating a second pulse sequence detecting the nuclear magnetic resonance signal at predetermined repetition time intervals; (4) acquiring a projection of the imaging section from the nuclear magnetic resonance signal detected in the first pulse sequence of the (3); (5) determining a similarity coefficient between the projection and the reference projection; (6) collecting the nuclear magnetic resonance signals used for the image reconstruction in the second pulse sequence when a value of the similarity coefficient is larger than a predetermined threshold value; and (7) repeating the (3) to the (6).

8) The inspection method using nuclear magnetic resonance according to the 7), wherein the first pulse sequence of the (1) is executed once.

9) The inspection method using nuclear magnetic resonance according to the 7), wherein the first pulse sequence of the (1) is repeated at the predetermined repetition time intervals, and an average of projections of the imaging section acquired from the nuclear magnetic resonance signals detected by repeating the first pulse sequence of the (1) is

obtained as the reference projection.

10) The inspection method using nuclear magnetic resonance according to the 7), further has, between the (2) and the (3), the steps of: (a) in the state that the living body breathes, repeating the first pulse sequence at the predetermined repetition time intervals; (b) determining frequency of appearance of the similarity coefficient between a projection of the imaging section acquired from the nuclear magnetic resonance signals detected by repeating the first pulse sequence of the (a) and the reference projection; and (c) deciding, as the predetermined threshold value, the similarity coefficient in which the sum of the frequency of appearance in a part in which the similarity frequency is close to 1 is 1/m of the sum of the frequency of appearance where m is a positive number of 3 or above.

11) An inspection method using nuclear magnetic resonance having the steps of applying a radiofrequency magnetic field and a magnetic field gradient to a living body placed in a static magnetic field to detect a nuclear magnetic resonance signal produced from the living body and using the detected nuclear magnetic resonance signal to perform image reconstruction of an imaging section, has the steps of: (1) in the state that the living body stops exhalation, executing a first pulse sequence detecting the nuclear magnetic resonance signal; (2) acquiring a reference projection

of the imaging section from the nuclear magnetic resonance signal detected in the first pulse sequence; (3) in the state that the living body breathes, repeating the first pulse sequence at predetermined repetition time intervals; (4) acquiring a projection of the imaging section from the nuclear magnetic resonance signal detected in the first pulse sequence of the (3); (5) determining a similarity coefficient between the projection and the reference projection; (6) determining a predetermined threshold value from frequency of appearance of the similarity coefficient; (7) in the state that the living body breathes, executing once the first pulse sequence and in the state that the living body breathes, repeating a second pulse sequence detecting the nuclear magnetic resonance signal at said predetermined repetition time intervals; (8) acquiring a projection of the imaging section from the nuclear magnetic resonance signal detected in the first pulse sequence of the (7); (9) determining the similarity coefficient between the projection of the (8) and the reference projection; (10) collecting the nuclear magnetic resonance signals used for the image reconstruction in the second pulse sequence when a value of the similarity coefficient of the (9) is larger than the predetermined threshold value; and (11) repeating the (7) to the (10).

12) The inspection method using nuclear magnetic resonance according to the 11), further has the step of

14

deciding, as the predetermined threshold value, the
similarity coefficient in which the sum of the
frequency of appearance in a part in which the
similarity frequency is close to 1 is 1/m of the sum of
the frequency of appearance where m is a positive
number of 3 or above.

13) An inspection method using nuclear magnetic
resonance having the steps of applying a radiofrequency
magnetic field and a magnetic field gradient to a
living body placed in a static magnetic field to detect
a nuclear magnetic resonance signal produced from the
living body and using the detected nuclear magnetic
resonance signal to perform image reconstruction of an
imaging section, has the steps of: (1) in the state
that the living body stops exhalation, executing a
first pulse sequence having a first time section
applying, to the living body, a slice select magnetic
field gradient having a positive polarity and a
radiofrequency magnetic field, a second time section
applying, to the living body, a readout magnetic field
gradient having a negative polarity, a third time
section detecting the nuclear magnetic resonance signal
in the state of applying the readout magnetic field
gradient having a positive polarity, and a fourth time
section applying, to the living body, the readout
magnetic field gradient having a negative magnetic
field; (2) one-dimensional inverse Fourier transforming
the nuclear magnetic resonance signal detected in the

first pulse sequence to acquire a reference projection
of the imaging section in the direction applying the
readout magnetic field gradient of the imaging section;
(3) in the state that the living body breathes,
executing once the first pulse sequence and in the
state that the living body breathes, executing a second
pulse sequence repeating, at predetermined repetition
time intervals, a pulse sequence having a fifth time
section applying, to the living body, the slice select
magnetic field gradient having a positive polarity and
the radiofrequency magnetic field, a sixth time section
applying, to the living body, respective magnetic field
gradients of a phase-encoding magnetic field gradient
and a readout magnetic field gradient having a negative
polarity, a seventh time section detecting the nuclear
magnetic resonance signal in the state of applying the
readout magnetic field gradient having a positive
polarity, and an eighth time section applying, to the
living body, the phase-encoding magnetic field gradient
having the opposite polarity of the polarity of the
phase-encoding magnetic field gradient applied in the
second time section and the readout magnetic field
gradient having a negative polarity, by changing the
magnitude of the phase-encoding magnetic field
gradient; (4) one-dimensional inverse Fourier
transforming the nuclear magnetic resonance signal
detected in the first pulse sequence of the (3) to
acquire a projection in the direction applying the

readout magnetic field gradient of the imaging section;
(5) determining a similarity coefficient between the
projection and the reference projection; (6) collecting
the nuclear magnetic resonance signals used for the
image reconstruction in the second pulse sequence based
on comparison of a value of the similarity coefficient
with a predetermined threshold value; and (7) repeating
the (3) to the (6).

14) The inspection method using nuclear magnetic
resonance according to the 13), further has the step of
collecting the nuclear magnetic resonance signals used
for the image reconstruction in the second pulse
sequence when a value of the similarity coefficient is
larger than a predetermined threshold value.

15) The inspection method using nuclear magnetic
resonance according to the 13), further has the steps
of: determining frequency of appearance of the
similarity coefficient and deciding, as the
predetermined threshold value, the similarity
coefficient in which the sum of the frequency of
appearance in a part in which the similarity frequency
is close to 1 is 1/m of the sum of the frequency of
appearance where m is a positive number of 3 or above.

16) The inspection method using nuclear magnetic
resonance according to the 13), wherein the first pulse
sequence of the (1) is executed once.

17) The inspection method using nuclear magnetic
resonance according to the 13), further has the step of

repeating the first pulse sequence of the (1) at the predetermined repetition time intervals, whereby an average of projections of the imaging section acquired from the nuclear magnetic resonance signals detected by

5   repeating the first pulse sequence of the (1) is obtained as the reference projection.

18) An inspection method using nuclear magnetic resonance having the steps of applying a radiofrequency magnetic field and a magnetic field gradient to a

10 living body placed in a static magnetic field to detect a nuclear magnetic resonance signal produced from the living body and using the detected nuclear magnetic resonance signal to perform image reconstruction of an imaging section, has the steps of: (1) in the state

15 that the living body stops exhalation, executing a first pulse sequence having a first time section applying, to the living body, a slice select magnetic field gradient having a positive polarity and a radiofrequency magnetic field, a second time section

20 applying, to the living body, a readout magnetic field gradient having a negative polarity, a third time section detecting the nuclear magnetic resonance signal in the state of applying the readout magnetic field gradient having a positive polarity, and a fourth time

25 section applying, to the living body, the readout magnetic field gradient having a negative polarity; (2) one-dimensional inverse Fourier transforming the nuclear magnetic resonance signal detected in the first

18

pulse sequence to acquire a reference projection of the imaging section in the direction applying the readout magnetic field gradient of the imaging section; (3) in the state that the living body breathes, repeating the first pulse sequence at predetermined repetition time intervals; (4) one-dimensional inverse Fourier transforming the nuclear magnetic resonance signal detected in the first pulse sequence of the (3) to acquire a projection in the direction applying the readout magnetic field gradient of the imaging section; (5) determining a similarity coefficient between the projection acquired in the (4) and the reference projection; (6) determining a predetermined threshold value from frequency of appearance of the similarity coefficient; (7) in the state that the living body breathes, executing once the first pulse sequence and in the state that the living body breathes, executing a second pulse sequence repeating, at the predetermined repetition time intervals, a pulse sequence having a fifth pulse sequence applying, to the living body, the slice select magnetic field gradient having a positive polarity and the radiofrequency magnetic field, a sixth time section applying, to the living body, respective magnetic field gradients of a phase-encoding magnetic field and a readout magnetic field gradient having a negative polarity, a seventh time section detecting the nuclear magnetic resonance signal in the state of applying the readout magnetic field gradient having a

19

positive polarity, and an eighth time section applying, to the living body, the phase-encoding magnetic field gradient having the opposite polarity of the polarity of the phase-encoding magnetic field gradient applied

5 in the second time section and the readout magnetic field gradient having a negative polarity, by changing the magnitude of the phase-encoding magnetic field gradient; (8) one-dimensional inverse Fourier transforming the nuclear magnetic resonance signal

10 detected in the first pulse sequence of the (7) to acquire a projection in the direction applying the readout magnetic field gradient of the imaging section; (9) determining the similarity coefficient between the projection acquired in the (8) and the reference

15 projection; (10) collecting the nuclear magnetic resonance signals used for the image reconstruction in the second pulse based on comparison of a value of the similarity coefficient determined in the (9) with the predetermined threshold value; and (11) repeating the

20 (7) to the (10).

19) The inspection method using nuclear magnetic resonance according to the 18), further has the step of collecting the nuclear magnetic resonance signals used for the image reconstruction in the second pulse

25 sequence when a value of the similarity coefficient is larger than the predetermined threshold value.

20) An inspection method using nuclear magnetic resonance having the steps of applying a radiofrequency

magnetic field and a magnetic field gradient to a living body placed in a static magnetic field to detect a nuclear magnetic resonance signal produced from the living body and using the detected nuclear magnetic resonance signal to perform image reconstruction of an imaging section, has the steps of: (1) executing a first pulse sequence detecting the nuclear magnetic resonance signal to acquire a reference projection of an imaging section as the reference of monitoring of heartbeat of the living body; (2) executing once the first pulse sequence detecting the nuclear magnetic resonance signal to acquire a projection of the imaging section used for the monitoring and repeating a second pulse sequence detecting the nuclear magnetic resonance signal to acquire an image of the imaging section at predetermined repetition time intervals; and (3) collecting the nuclear magnetic resonance signals used for the image reconstruction in the second pulse sequence based on a similarity coefficient between the projection and the reference projection.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGS. 1(A) to 1(B) are diagrams showing a pulse sequence of a GE method of a prior art;

FIGS. 2(A) to 2(B) are diagrams of assistance in explaining ECG gating of a prior art;

FIG. 3 is a diagram showing a construction example of a nuclear magnetic resonance imaging

apparatus to which the present invention is applied;

FIG. 4 is a diagram showing echo-acquiring timing of an embodiment of the present invention;

FIG. 5 is a diagram of assistance in explaining the basic form of a pulse sequence of an embodiment of the present invention;

FIGS. 6(A) to 6(C) are diagrams showing the breathing monitoring result of an embodiment of the present invention;

FIG. 7 is a diagram of assistance in explaining an example of an actual echo-acquiring sequence according to the present invention;

FIG. 8 is a diagram showing an echo-acquiring flow according to the present invention;

FIG. 9 is a diagram showing a threshold value determining method according to the present invention;

FIG. 10 is a diagram showing echo-acquired results according to the present invention;

FIG. 11 is a diagram of assistance in explaining linear correlation coefficients according to the present invention; and

FIGS. 12(A) to 12(C) are diagrams showing a heartbeat monitoring method according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

An embodiment of the present invention will be described below in detail with reference to the

drawings.

FIG. 3 is a block diagram showing the schematic construction of a nuclear magnetic resonance imaging apparatus. In FIG. 3, the numeral 101 denotes a magnet for generating static magnetic field; the numeral 102, a coil for generating magnetic field gradient; and the numeral 103, a subject (living body). The subject 103 is placed in a static magnetic field space generated by the magnet 101. A sequencer 104 sends a command to a power supply for magnetic field gradient 105 and a radio frequency magnetic field generator 106 to generate a magnetic field gradient and a radiofrequency magnetic field, respectively. The radiofrequency magnetic field is applied via a probe 107 to the subject 103. A signal produced from the subject 103 is received by the probe 107 to be detected by a receiver 108. A nuclear magnetic resonance frequency as the reference of detection (hereinafter, referred to as a detection reference frequency) is set by the sequencer 104. The detected signal is sent to a computer 109 to perform signal processing such as image reconstruction therein.

The result is displayed on a display 110. When necessary, the detected signal and measurement conditions can also be stored into a storage medium 111. An ECG 114 connected to the sequencer 104 is in the static magnetic field space so as to measure an ECG of the subject 103. The measured ECG is fetched into the

23

sequencer 104. When static magnetic field uniformity must be adjusted, shim coils 112 are used. The shim coils 112 are constructed by plural channels to which an electric current is supplied from a shim power supply 113. When adjusting the static magnetic filed uniformity, an electric current flowed to the shim coils is controlled by the sequencer 104. The sequencer 104 sends a command to the shim power supply 113 to generate an additional magnetic field to correct static magnetic field non-uniformity from the coils 112.

The sequencer 104 generally performs control so that the respective units are operated at programmed timing and intensity. The program into which the timing and intensity of the radiofrequency magnetic field, magnetic field gradient and signal reception are described is called a pulse sequence.

Respiratory monitoring according to the present invention is performed by calculating a similarity coefficient between a reference projection of an imaging section and a projection acquired during monitoring. The similarity coefficient is a coefficient expressing the similarity of two projections. It is 1 when the two projections are the same and is monotonously reduced as the similarity is lowered.

The respiratory motion of a subject is cyclic. When the phase of breathing during monitoring is close to the phase of breathing at acquiring a reference projection, a similarity coefficient is close to 1 and

is smaller as it is away from the phase of breathing of the reference projection. When a reference projection is acquired in the state of breathing in (at inspiration), a similarity coefficient during

5   monitoring is gradually larger at inspiration to be close to 1 and is gradually smaller at exhalation. When a reference projection is acquired in the state of breathing out (at exhalation), a similarity coefficient during monitoring is gradually larger at exhalation to

10   be close to 1 and is gradually smaller at inspiration.

As the similarity coefficient, a linear correlation coefficient can be used. The value of points of a reference projection is x_i, and the value of points of a projection acquired during monitoring is y_i.

15   Linear correlation coefficient r_1 when i is 1, ..., N is given by the following formula.

$$r_1 = \frac{\sum_i (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_i (x_i - \bar{x})^2}\sqrt{\sum_i (y_i - \bar{y})^2}}$$

.... (1)

where $\bar{x}$ is an average of x_i and $\bar{y}$ is an average

20   of y_i.

Alternately, using inner product a given by the following formula,

$$a = |\vec{x}||\vec{y}|\cos\theta = \sum_i x_i y_i$$

.... (2)

25   where $\vec{x}$ and $\vec{y}$ are vectors having x_i and y_i as

2 5

components, respectively, and θ is an angle of $\vec{x}$ and $\vec{y}$

Approximately, r_2 expressed by the following formula may be used.

$$r_2 = \cos\theta = \frac{\sum_i x_i y_i}{|\vec{x}||\vec{y}|}$$

5   .... (3)

The integrated value of the intensity of a projection is hardly changed by breathing. When two projections are considered to be multidimensional vectors, whether the projections are similar can be
10   expressed depending on that the orientations of the vectors are close to each other. The similarity can be concluded to be r_2.

Using either coefficient, when the two projections are the same, a coefficient is 1. As the
15   similarity is lowered, the coefficient is smaller.

In general, there is a significant difference between the motion at inspiration in breathing in a rest state and the motion of deep breathing. As compared with this, a difference between exhalation in
20   a rest state and exhalation at the end of breathing out is small. The degree of freedom of the depth of deep breathing is large. The degree of freedom of exhalation is small. A projection at exhalation is used for a reference projection of breathing monitoring, which
25   tends to obtain a more stable result.

The relation between breathing and the operation of the sequencer when monitoring respiratory motion of

a subject by the imaging apparatus of FIG. 3 is shown in FIG. 4. The subject breathes out slowly and stops breathing at the end of it. During stopping breathing, the sequencer executes the pulse sequence shown in FIG.

5 5 to measure one echo which is then one-dimensional inverse Fourier transformed. The acquired projection is a reference projection.

FIG. 5 shows the basic form of a pulse sequence for acquiring breathing monitoring information by the

10 imaging apparatus of FIG. 3 according to the present invention. The pulse sequence is in a form that the phase-encoding pulse (Gy pulse) is removed from the pulse sequence of FIG. 1. An echo 220 measured by the pulse sequence is one-dimensional inverse Fourier

15 transformed to acquire a projection of an imaging section in a readout direction (Gx direction).

The sequencer executes the sequence of FIG. 5 at fixed time intervals after acquiring a reference projection to create a projection. The computer

20 calculates a linear correlation between the projection and the previously acquired reference projection. During this, a subject performs general breathing.

When acquiring the reference projection, measurement of one echo is generally sufficient. When

25 including a heart in an echo-acquired section, a projection is largely changed by heartbeat. In this case, the pulse sequence of FIG. 5 is executed repeatedly to measure plural echoes. The echoes for one

heartbeat are averaged to remove the influence of the heartbeat. When a reference projection is acquired by averaging and individual projections during monitoring are influenced by heartbeat so that a linear

5 correlation coefficient is not stable, a moving average of the linear correlation coefficients is calculated to enable stable monitoring.

FIG. 6 shows an example of an tomographic image acquired by actual measurement and linear correlation

10 coefficients. As shown in FIG. 6(A), the image shows the transverse section of a chest, the right and left directions (the up-and-down direction on the sheet in the drawing) of the transverse section is a readout direction, and a project direction is vertical to the

15 readout direction (in the right-and-left direction on the sheet in the drawing). The projection shown in FIG. 6(B) is acquired for 30 seconds at 80 milliseconds intervals. The graph of the linear correlation coefficients (similarity coefficients) shown in FIG.

20 6(C) shows the result of a moving average of 15 linear correlation coefficients. From the graph, the change in the linear correlation coefficient in synchronization with breathing of a subject can be read. The linear correlation coefficient is close to 1 at exhalation and

25 is smaller at inspiration. It is found that respiratory motion of the subject can be monitored using the linear correlations.

A method for acquiring an image without motion

artifact while monitoring breathing in real time by the above method will be described. In general, the stop period of motion at exhalation is longer than that at inspiration. In this method, echoes are measured only in a period in which breathing of a subject is decided to be exhalation to reconstruct an image.

As shown in FIG. 7, as an actual pulse sequence, each time pulse sequence B of FIG. 1 is executed n times, pulse sequence A of FIG. 5 is executed once. n depends on TR and the time resolution of breathing monitoring. For example, when at TR of 5ms, the time resolution of breathing monitoring is 80ms, n is 15.

An echo-acquiring flow will be described according to FIG. 8. As pulse preparation, the echo-acquiring sequence of FIG. 5 is used to acquire a projection at exhalation or inspiration of a subject, creating a reference projection (step 801). The case of using the projection at exhalation will be described below.

The pulse sequence of FIG. 7 is executed to estimate a change in the linear correlation of respiratory motion of the subject. In other words, the pulse sequence of FIG. 7 is executed to calculate a linear correlation between the projection acquired in first half part A and the reference projection. This is executed for sufficient time (for example, for 30 seconds) to create a histogram of the calculated linear correlations. From this histogram, there is determined

linear correlation value Rth in which frequency of appearance of a part in which the linear correlation is close to 1 is 1/m (m is a positive number.) of the entire frequency of appearance (step 802). During this, echoes acquired in latter half part B of the pulse sequence are discarded.

In the later measurement, the pulse sequence of FIG. 7 is used to acquire a tomographic image of the subject while monitoring breathing. The A is executed to acquire a projection to calculate a linear correlation coefficient between it and the reference projection (step 807). When the value is larger than the Rth, exhalation is decided (step 803). Only in this case, echoes for image reconstruction are measured (step 804). When not deciding exhalation, the sequence is executed and echoes are discarded or not measured (step 805). This is continued until echoes necessary for image reconstruction are acquired (step 806).

The magnitude of the influence of motion to image reconstruction depends on the m. As the m is larger, the influence of motion is smaller and an image having good quality can be acquired. In general, when the m is 3 or above, sufficient image quality can be acquired.

FIG. 10 shows the echo-acquired results of the transverse section of the chest at m of 6, 3 and 1. Blurring caused when not using breathing monitoring (m of 1) is found to be suppressed when m of 3 and 6. As

the m is larger, the image quality is better.

A method for monitoring motion (heartbeat) of a heart using the linear correlation coefficient of a projection will be described. For heartbeat monitoring, a projection created from one echo acquired immediately after R wave as a reference projection is used. As a linear correlation coefficient acquired during monitoring, a value close to 1 immediately after the R wave can be obtained. Unlike the breathing monitoring, generally, a moving average need not be calculated. When monitoring only heartbeat without performing breathing monitoring, breath-hold need not be performed when acquiring the reference projection.

FIG. 11 is a graph showing the case that the change in the linear correlation coefficients in which a moving average is not calculated, acquired as in FIG. 6(C) using the reference projection created from one echo acquired immediately after the R wave. In this case, the linear correlation coefficient is changed in a slow period according to respiratory motion and the linear correlation coefficient is instantly large in a short period according to heartbeat. Since the reference projection is created from the echo immediately after the R wave, the time at which the linear correlation coefficient is instantly large coincides with the R wave. The data is used to detect peak positions to detect the R wave, monitoring heartbeat.

The peak positions can be detected as positions in which a first derivative of the graph of FIG. 11 is 0 and a second derivative is negative. FIG. 12(A) is a graph enlarging part of FIG. 11 (The peak positions are indicated by O in the drawing.). FIGS. 12(B) and 12(C) show the first derivative result and the second derivative result of FIG. 12(A). From the drawings, the peak positions coincide with the positions in which a first derivative is 0 and a second derivative is negative.

Using this method, heartbeat can be monitored without using an ECG. The operation of the case of executing this in the apparatus of FIG. 3 is as follows.

As shown in FIG. 4, the subject breathes out slowly and stops breathing at the end of it. During that, the sequencer executes the pulse sequence of FIG. 5 to measure one echo. A projection acquired by one-dimensional inverse Fourier transforming this is a reference projection. Thereafter, the subject performs general breathing. The sequencer executes the pulse sequence of FIG. 5 at fixed time intervals to create a projection. The computer calculates a linear correlation between the projection and the previously acquired reference projection. A peak position is detected by the above-described method. When detecting the peak, the computer sends a trigger of the R wave to the sequencer. The sequencer uses the trigger as a substitute for a trigger from an ECG of the prior art.

For example, in the case of cardiac imaging using ECG gating described in the prior art, phase encoding is changed in synchronization with the trigger.

Using the heartbeat monitoring according to the present invention as a substitute for an ECG, trouble for putting on an ECG before inspection can be eliminated to improve the inspection throughput.

In the above-described embodiment, a reference projection is acquired before the echo-acquiring sequence of a projection. In the present invention, a reference projection may be acquired after terminating the echo-acquiring sequence of a projection. In this case, however, all echoes are measured and stored to calculate a similarity coefficient in post-processing, selecting the echoes according to this. The number of echoes measured and stored is m times the number necessary for reconstruction.

As described above in detail, according to the present invention, an echo in an exhalation period can be acquired. A significant effect of suppressing blurring of an image caused by respiratory motion can be achieved. In addition, heartbeat is monitored by the present invention. An ECG need not be put on and diagnosis can be conducted more simply.

The present invention can realize an inspection apparatus using nuclear magnetic resonance which can execute multi-slice and multi-frame cardiac imaging without giving any load on a subject.